

Why Photons Are Not Slow*

February 14, 2012

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Abstract

We discuss to what extent the simplest attempt to reconcile the OPERA experiment with Special Relativity is excluded (except maybe in very contrived frameworks), assuming that the Special Relativity formalism holds, but with a larger limiting speed c_l , while the photon moves at slower speed (which may involve the presence of an “aether”). We take into account the most recent Michelson-Morley type experiments.

The recent claim by OPERA of “faster than light” neutrinos [1] has brought a number of comments. It is particularly disturbing in the fact that it seems to disagree with the standard presentation of Special Relativity, where the limiting speed is the photon speed. In this framework, the observation seems to enter in contradiction with a number of well-established facts about Special Relativity. Just to name one, the dilatation of time is checked everyday in cosmic rays and accelerator measurements. This, without even mentioning the issue of causality.

The experiment rests in fact on an indirect comparison of the neutrino speed (measured through a timing which uses the speed of the electromagnetic radiation) and the distance (also determined by photon-based measurements, including the GPS signals, of frequency within the GHz range). The simplest possibility which springs to mind, and which would bring the minimal modification, is that the effect is not due to neutrinos exceeding the limiting speed c_l , but to assume that for some reason, photons travel at a speed $c < c_l$. By far the simplest way to achieve this is through an hypothetical photon mass (at the cost of sacrificing gauge invariance, and electric charge conservation); however existing limits on the photon mass show that any effect would be completely negligible with regard to the current observation.⁴ It would furthermore remain sensitive to the Michelson-Morley test described below.

An alternative could be a breaking of Lorentz invariance, but could more simply be blamed on some medium, or “aether”, in the Earth neighbourhood, with an *ad hoc* refraction index n . The photon’s speed in such a medium could be c_l/n , with c_l the “true limiting speed” [3, 4]. However unaesthetic such an “aether” may be, let us remember that other examples of such local or global structures exist, and provide a preferred frame: dark matter halos, CMB radiation, etc. Although these are very unlikely to account for such an effect, it is a legitimate question to consider this possibility.

For this purpose we assume that Special Relativity is preserved (with c replaced by c_l), and that the Einstein velocity-addition formula can then be used to evaluate the speed of light in our reference frame. We then assume that our frame moves at a speed v with respect to a medium in which the photon speed

*Presented at the “Fundamental Interactions IAP meeting”, Brussels, February 3rd, 2012.

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⁴The OPERA result for GPS photons (in the GHz range) would require $m_\gamma > 10^{-8}$ eV while the current limit is $m_\gamma < 10^{-18}$ eV [2].

c is defined (we set $c = c_l/n$). In a direction transverse to v , light velocity remains equal to $c_\perp = c_l/n$, while in a direction parallel to v we have

$$\begin{aligned} c_\parallel^+ &= \frac{\frac{c_l}{n} + v}{1 + \frac{v}{nc_l}} \\ c_\parallel^- &= \frac{\frac{c_l}{n} - v}{1 - \frac{v}{nc_l}}, \end{aligned} \quad (1)$$

where $+$ and $-$ stand for the speed along or against v . This is of course very standard. Nevertheless it is of interest to see how this scenario confronts with state-of-the-art measurements of the anisotropy of the speed of light.

In recent experiments of Michelson-Morley type [5],[6], it has been shown that the local maximal anisotropy can not exceed

$$(\Delta c/c)_{exp} \sim 1 \times 10^{-17}. \quad (2)$$

We emphasize that this represents an improvement of about one order of magnitude compared to previous measurements (see for instance [7]). In these experiments the parallel “average” velocity is measured

$$c_\parallel = \frac{\text{”path length”}}{\text{”round trip time”}} = \frac{2L}{L/c_\parallel^+ + L/c_\parallel^-}$$

since the experiment is based on a forth and back movement of light in a resonator. This average velocity c_\parallel is

$$c_\parallel = \left(\frac{\frac{c_l}{n} - \frac{nv^2}{c_l}}{1 - \frac{v^2}{c_l^2}} \right).$$

The theoretic resultant anisotropy which has to be compared with $(\Delta c/c)_{exp}$ is

$$\frac{\Delta c}{c} = \frac{c_\perp - c_\parallel}{c_\perp} = \frac{v^2}{c_l^2} \frac{n^2 - 1}{1 - \frac{v^2}{c_l^2}}.$$

We can take $n = 1 + \delta$ with $\delta \ll 1$ and obtain at first order in δ (we also assume $(v/c)^2 \ll \delta$)

$$\frac{\Delta c}{c} \approx 2 \frac{v^2}{c_l^2} \delta \approx 2 \frac{v^2}{c^2} \delta. \quad (3)$$

As expected, the effect we are considering is second order in the velocity v .⁵

Now we would like to compare the above limit (2) to the expectation from the OPERA experiment.⁶ For this, a choice must still be made: which relative speed v should we take? We will further discuss this question later, but for the moment just take a rather “conservative” approach, associating v to the rotation speed of the Earth on its axis at the experiment point.⁷

The OPERA data would correspond to [1]⁸

$$\delta \approx \frac{c_l - c}{c} \approx 2.37 \cdot 10^{-5}. \quad (4)$$

⁵Second order in v/c comes from the compensation of the first order effects in the “mean” velocity.

⁶One should of course remember that the distance measurements in OPERA largely depend upon GPS measurements, at a frequency between 1 and 2 GHz, while the most recent Michelson-Morley experiment is performed with near-infrared photons ~ 280 THz. However a direct comparison of the speed of light at these wavelengths should be comparatively easy (we do not refer here to the ionospheric propagation effects of GPS signals, which are already taken into account by the experiment).

⁷Clearly the other “natural” choices of frame lead to much stronger exclusions. Modern laboratory tests of Lorentz invariance are usually presented within the framework of the so-called minimal Standard Model Extension [8] and adopt a reference frame for the speed of light that is centered on the Sun, so that v is (essentially) the Earth orbital velocity $v_\oplus/c \approx 10^{-4}$. In this case the quoted limit on δ (noted κ_{tr} and corresponding to $\Delta c/c \lesssim 10^{-16}$ [9, 10]) is $\delta \lesssim 7 \cdot 10^{-9}$.

⁸The precise value is $(2.37 \pm 0.32(stat.)^{+0.34}_{-0.24}(sys.)) \cdot 10^{-5}$.

When compared to the rotation speed of the Earth, we see that it takes the most recent Michelson-Morley experiments to (virtually) exclude this possibility, unless the medium is in some way dragged into the Earth rotation. Indeed, with $v = 465 \cos 53^\circ \text{ m}\cdot\text{s}^{-1}$, where $465 \text{ m}\cdot\text{s}^{-1}$ (*i.e.* $v/c = 1.55 \cdot 10^{-6}$) is the equatorial rotation speed of the Earth, and the cosine takes into account the Berlin latitude where the Michelson-Morley experiments took place, we have

$$\left. \frac{\Delta c}{c} \right|_{\text{OPERA}} \approx 4.13 \cdot 10^{-17} \quad (5)$$

which shows a clear tension with (2).⁹ We note that [5] predicts improved constraints (at the 10^{-20} level) for the near future, which could allow one to strengthen this conclusion.¹⁰

It is sometimes argued that the photon speed could be modified in an “invariant” way, by which it would escape the above limit, keeping its value in all frames (see for instance [3]), while different from the overall limit c_l . This view is very different from the already discussed “photon mass”, and difficult to reconcile with the Lorentz transformations, for which only c_l is preserved. It would thus necessitate a much more fundamental re-formulation of Special Relativity (see for instance [12]).

We return now briefly to the question of the “aether” approach, in relation to the choice of the relative speed v in Eq.(3). Should it be necessary to resuscitate such “aether”, one obvious possibility would be to relate it to dark matter or dark energy. Because of (5) we need to take the worst possible case, and thus we must accept the possibility that such medium (in particular if it is linked to some dark matter effects [13]) is carried along with the Earth and the Solar system in its Galactic motion, under the effect of gravitation or some hypothetical interaction between dark and ordinary matters. This would depart from the usual assumption of a nearly-spherical galactic halo of dark matter with low angular momentum, or with the dark matter velocity distributions assumed in dark matter direct detection searches (see *e.g.* [14]). However the assumption of this medium co-moving with the Earth inside the Solar system and the Galactic dark matter halo is at odds with Supernovae data¹¹: to reconcile the OPERA measurement with the nearly simultaneous arrival of light and neutrinos from the Supernova SN1987a, we would need to assume that the medium is largely absent between the Solar system and the Magellanic clouds, in contradiction with the alleged role of dark matter in the Galaxy. Also, keeping a local medium static with respect to the Earth surface seems difficult without requiring some (possibly detectable) friction with ordinary matter. Altogether this scenario seems rather baroque.

Acknowledgements

This work is supported in part by the Belgian Science Policy (IAP VI/11: Fundamental Interactions), the IISN and by an ARC (“Beyond Einstein: fundamental aspects of gravitational interactions”). We thank many colleagues for discussions, in particular Petr Tinyakov, Gaston Wilquet and Pierre Vilain, which prompted this remark.

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⁹A more precise limit would probably benefit from a detailed re-analysis of the recent Michelson-Morley data, in the spirit of [10].

¹⁰We are aware that stronger constraints on a possible refraction index for photons exist in the literature, in particular based on colliders data (see [11] and references therein). These limits generally rest on supplementary assumptions and are thus less direct than the limits based on Michelson-Morley type experiments.

¹¹Not to mention the possible tension between this scenario and astronomical determinations of the speed of light (see for instance [15]), an issue we do not dwell in here.

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